ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING ACCEPTABLE INDOOR AIR QUALITY

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PAPER 11

AIR INFILTRATION AND AIR TIGHTNESS TESTS IN EIGHT U.S. OFFICE BUILDINGS

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ABSTRACT

The National Bureau of Standards has undertaken the development of diagnostic test methods for evaluating the thermal integrity of federal office buildings. The purpose of this program is to develop test procedures which can be used for 1.) the verification of the thermal specifications of recently constructed federal buildings, 2.) the determination of applicable retrofit measures to existing buildings and 3.) the post evaluation of retrofit work. As part of this project, eight federal office buildings ranging in size from 3000 m^2 to 45,000 m^2 have been tested for their air infiltration characteristics. These buildings are located in Anchorage, AK; Huron, SD; Fayetteville, AR; Pittsfield MA; Springfield, MA; Norfolk, VA; Columbia, SC and Ann Arbor, MI. Tracer gas tests have been performed in these buildings during the fall, winter and spring in order to evaluate both the ventilation of these buildings during occupied periods and the natural air leakage under various weather conditions. Fan pressurization tests have been performed on these buildings using the supply and exhaust fans of the building and a tracer technique to measure the air flow induced by the HVAC fans. In addition, during the winter an infrared thermographic inspection of the buildings was performed which revealed the sites of building leakage.

1. INTRODUCTION

It has been found in the United States that many new buildings which were designed to energy conservation standards and specifications do not after construction perform according to the design due to either poor workmanship or a misunderstanding of the construction specification. It is difficult to determine by normal inspection techniques whether a building under construction will meet its design specification. There exist a need for in situ and nondestructive measurement techniques to verify the thermal integrity of the envelope system of office buildings under construction and during the post occupancy evaluation period when the building is under warrantee. In this period, thermal defects which can be identified and located would be the responsibility of the contractor to correct before departing from the site. Existing buildings degrade with age and require periodic maintenance. The potential for serious deterioration in the building will often produce thermal anomalies long before serious damage has occurred. The detection of these anomalies can lead to corrective action before costly repairs are required. To assure the quality of remedial actions taken to improve existing office buildings, inspection techniques are also required. Recognizing this situation, the General Services Administration (GSA) started a project at the National Bureau of Standards (NBS) to develop, assess and demonstrate measurement methods which would be applicable to its requirements for evaluating the thermal integrity of its office buildings. The inspection techniques being evaluated by NBS are: ground-based infrared thermographic surveys, aerial infrared surveys, tracer gas air infiltration measurements, pressurization tests for determining the tightness of the building envelope, energy audits using spot radiometers, quantitative measurement of the thermal resistance of sections of the building envelope using heat flow meters, a portable calorimeter box design by the National Research Council of Canada and an envelope thermal testing unit developed by Lawrence Berkeley Laboratory and the individual testing of the tightness of building components using pressurization. A description of these measurement techniques and this research program can be found in reference [1]. This paper will discuss the results of the measurements performed on eight federal office buildings as they related to air infiltration and building tightness.

2. DESCRIPTION OF THE EIGHT FEDERAL OFFICE BUILDINGS

The eight federal office buildings are located in the cities shown in the map in figure 1. In general these are new (less than 3 years old) buildings constructed to the U.S. federal energy guidelines of less than 630 MJ/M^2 per year of on-site energy and less than 1200 MJ/M^2 per year of off-site energy. The exception to this is the federal building in Fayetteville, AR which is 7 years old and was built before the energy guidelines for new federal office buildings was in effect. Though these buildings tend to perform better than most existing federal office buildings, none has meet the energy guidelines during its first few years of occupancy. For the purpose of this study the buildings in Anchorage, AK; Springfield, MA; Norfolk, VA, and Columbia, SC are considered large office buildings (over 10,000 M^2 of occupiable area). Columbia has a height of 15 stories, Norfolk, 8 stories; Anchorage between 2 to 6 stories depending on the module; and Springfield, 5 stories. The buildings in Pittsfield, MA; Huron, SD; Ann Arbor, MI and Fayetteville, AR are consider as small office buildings for the purpose of the study (lessthan 10,000 M^2 occupiable area). These small office buildings range in height from 2 to 5 stories. A summary of the characteristics of the buildings is given in table 1. Schematics and a photograph for each building are given in figures 2 to 9. All but two of the buildings have variable volumeair handlers in the major zones of the buildings. They are heated by perimeter heating systems which are usually hydronic. The building in Columbia has two air perimeter heating systems. In the building in Norfolk heaters and air conditioners have been added to the air system on floors which proved difficult to heat or cool. They all have central chiller systems for cooling the core spaces of the buildings. The buildings in Anchorage and Springfield have underground garages. The building in Norfolk has an exterior garage which occupies part of floors 1 to 4.

3. AIR INFILTRATION AND VENTILATION RATES

The air infiltration under natural conditions was measured using sulfur hexafluoride (SF_6) as a tracer. This test was designed for each building to produce a measure of the total air infiltration of the building and the air infiltration of the major zones of the building. Sample tubing and injection tubing was installed in each zone along with wiring for measurng interior temperatures, the status of the building's HVAC fans and for a weather station (wind speed, wind direction and exterior temperature). The automatic air infiltration system [2] previously designed by NBS for large buildings was installed in each building for a period of about a week during the fall, winter and spring (three automated air infiltration systems were used on this project). Tests were performed both during periods of occupancy and non-occupancy, and with the dampers opened and closed. To date, tracer gas infiltration meaurements have been made for a total of about 200 hours in each building. The air sample locations for these tests are given in table 2.

The results of these measurements are summarized in tables 3 to 10 and figures 10 to 12. The data has been categorized in the ventilation rates experienced during occupied periods, infiltration rates for wind speed less that 2.5 M/S and infiltration rates for wind speed greater than 2.5 M/S. Tables 3 to 10 give the average air exchange rates for various temperature bins. A study of the data in figure 10 and tables 3 to 10 show three distinct patterns in the ventilation rates in the eight buildings. The building in Huron shows little change in the ventilation rate during occupied periods over all temperature bins with the possibility that the ventilation rate raises for the temperature bin 10 to 20 °C. The building in Anchorage shows this raise in temperature clearly. The buildings in Norfolk and Ann Arbor have low ventilation rates at both low and high temperatures with increasing ventilation rates in the temperature bin 10 to 20 °C. This increase is due to use of outdoor air of cooling of the building. The building in Springfield has a fairly constant ventilation rate in the temperature bin 10 to 20 °C and an increasing ventilation as the temperature decreases.This is probably due to the increase in infiltration as the temperature decreases for this building (figures 11 and 12). These trends in the data are indicated by the dotted lines in figure 10. The minimum ventilation rates for these buildings are given in table 11. As can be seen by examining the data, some of these building under certain weather conditions violate these minimum ventilation rates.

The air infiltration rates for some of the buildings are show in figures 11 and 12. In general, though there is considerable variation in the data, it can be seen that lower exterior temperatures produce higher air infiltration rates and higher wind speeds produce higher air infiltration rates. Fitting a regression line to the data in figures 11 and 12 produce the following relationships between the temperature and air infiltration rates:

<u>Wind Speed less than 2.5 M/S</u>

Norfolk:

$$I = 0.59 - 0.0072\ T_{out} \qquad r^2 = 0.38$$

Springfield:

$$I = 0.58 - 0.0192\ T_{out} \qquad r^2 = 0.20$$

Ann Arbor:

$$I = 0.70 - 0.0056\ T_{out} \qquad r^2 = 0.03$$

Huron:

$$I = 0.20 - 0.0058\ T_{out} \qquad r^2 = 0.40$$

<u>Wind Speed Greater Than 2.5 M/S</u>

Norfolk:

$$I = 0.64 - 0.0085\ T_{out} \qquad r^2 = 0.60$$

Ann Arbor:

$$I = 0.80 - 0.0115\ T_{out} \qquad r^2 = 0.15$$

Huron:

$$I = 0.24 - 0.0021\ T_{out} \qquad r^2 = 0.07$$

4. BUILDING TIGHTNESS MEASURIZATIONS

The building tightness of the eight federal office buildings were tested using whole building fan pressurization and tracer gas techniques. The fan pressurization tests were performed during the fall of 1982 on seven of the eight federal buildings using the building's HVAC system fans. It was not possible to pressurize the federal building in Fayetteville because the outside air duct could not bring in a sufficient volume of air due to its limited size. In principle this building could be pressurized by use of an external fan however the shipment of this fan to Fayetteville was judged to be too expensive.

The results of the pressurization tests and the fall tracer gas air infiltration measurements (dampers closed) are shown in table 12. The most notable aspect of these data is the tightness of the buildings from the pressurization measurements. The pressurization test results are the air flow rates into the buildings, in units of building volumes or exchanges per hour, required to sustain a 25 Pascal (Pa) pressure difference between inside and outside. These flow rates are significantly larger than the ventilation rates during normal building operation or infiltration rates induced by weather. The 50 Pa (0.2 inches of H_2O) exchange rates of the buildings are roughly 1.5 times the 25 Pa (0.1 inches of H_2O) rates shown in the table. These 50 Pa leakage rates are very low compared to homes. U.S. homes range from about 5 volumes per hour (very tight) to greater than 20 (very leaky). Swedish and Canadian homes are being built with 50 Pa flow rates of less than 2 volumes per hour. Thus, the 50 Pa flow rate of these federal buildings correspond to very tight homes.

From the data in table 12, it can be seen that there is correlation between the pressurization measurements and the tracer gas test results. Bearing in mind that the tracer gas results are preliminary and made only under approximately the same weather conditions, infiltration rates have been plotted against pressurization results in figure 13. The correlation between the two measurements appears to be fairly strong. The slope of a line passing through all the points is roughly 0.5. If one adjusts the 25 Pa flows to 50 Pa flows using the rough correction factor of 1.5, then the slope of infiltration against 50 Pa flow is about 1/3. This compares to the slope for residential buildings which is about 1/20.

In comparing the pressurization test results of the federal buildings to each other and to residential buildings, the important factor of surface to volume ratio arises. Figure 14 shows the surface to volume ratios (S/V) for the federal buildings and two sample homes. The 1-story house is assumed to have a 120 M^2 square floor area and 2.5 M ceilings. The 2-story home also has a square floor plan with 100 M^2 on each floor and a 5 M building height. We see in the figure that the large sizes of the federal buildings generally lead to lower values of S/V than for homes. The Ann Arbor building is an exception due to its particular design.

One may adjust the pressurization test results in table 12 to take into account the different values of S/V amoung the buildings. Table 12 gives the 25 Pa leakage rate in building volumes per hour. This number divided by S/V, yields the 25 Pa flow rate in m^3/hr per m^2 of exterior surface area. This second flow rate is more of a measure of "construction quality" than the first flow rate. Figure 15 compares these two measures of leakiness. The vertical scale on the left shows the 25 Pa flows in exchanges per hour for the seven federal buildings and the two sample houses (2.0 exchanges/hr at 50 Pa, extremely tight). The vertical scale on the right shows the 25 Pa flows in $m^3/hr\text{-}m^2$ as discussed above. We see that in moving from exhcanges/hr to $m^3/hr\text{-}m^2$ the tightness ranking of the buildings changes significantly. Also, the spread in the leakage values using the second measure is larger than the spread in exchanges per hour. The most significant change occurs in the Ann Arbor building which is of average tightness as measured by exchanges per hour but is the tightest building in terms of $m^3/hr\text{-}m^2$. Thus, the Ann Arbor building has the tightest construction per m^2 of wall area, but its design leads it to appear relatively leakier than many of the other buildings as measured by the flow in exchanges per hour.

5. LOCATION OF AIR INFILTRATION SITES USING THERMOGRAPHY

Each of the federal office buildings was inspected using an infrared thermographic system during the winter. These inspections were performed from both the exterior and interior of the buildings at night. These inspection show the location of several classes of air infiltration sites in these buildings. These are summarized in table 13. Figure 16 shows some examples of the thermograms produced. A more complete discussion the the results of the thermographic surveys can be found in references 3 and 4.

6. CONCLUSIONS

The results of this study show that it is possible to perform air infiltration and building tightness measurements even in large buildings. In modern U.S. office buildings, the air infiltration rates due to environmental factors tend to be low and these office building can be classified as tight. During the operation of these buildings, there are periods of time when the buildings will have low ventilation rates which are below the accepted minimum requirements for occupied office buildings.

ACKNOWLEDGMENTS

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[1] Grot, R.A., Burch, B.M., Silberstein, S.S., and Galowin, L.S., Measurement Methods for Evaluation of Thermal Integrity of Building Envelopes, NBSIR 82-2605

[2] Grot, R.A., Hunt, C.M., and Harrje, D.T., Automated Air Infiltration Measurements in Large Buildings, in proceeding of first Air Infiltration Centre Conference, AIC, Bracknell, U.K., 1980

[3] Grot, R.A., Chang, Y.L., Persily, A.K. and Fang, J.B. Data from NBS Thermal Integrity Tests on Eight GSA Federal Office Buildings, NBSIR - in preparation

[4] Chang, Y.L. and Grot, R.A., The Assessment of the Thermal Integrity of Federal Office Building Infrared Thermography, to be published in proceedings of Thermosense VI, SPIE.

	Area (M^2)	Volume (M^3)	Zones	HVAC Type
Anchorage	48,470	174,000	6	VAV
Springfield	14,560	75,300	3	VAV*
Columbia	21,600	109,000	3	VAV*
Norfolk	18,570	60,300	2	VAV*
Pittsfield	1,860	8,520	2	CV
Huron	6,910	27,500	2	VAV*
Ann Arbor	5,270	33,400	3	VAV*
Fayetteville	3,660	20,400	6	CV

VAV - Variable Volume CV - Constant Volume

* Lobbies have constant volume air handlers

Table 1. Summary of Building Characteristics for Eight Federal Office Buildings

Anchorage
1. Module A
2. Module B
3. Module C
4. Module D
5. Module E
6. Module F
7. 5th Floor Module C
8. 3rd Floor Module C
9. 1st Floor Module C

Columbia
1. HVAC Return
2. 13th Floor
3. 11th Floor
4. 9th Floor
5. 7th Floor
6. 5th Floor
7. 3rd Floor
8. 1st Floor & Basement
9. Lobby
10. Courthouse

Springfield
1. North Return
2. South Return
3. Atrium/Lobby
4. 5th Floor - North
5. 4th Floor - North
6. 3rd Floor - North
7. 2nd Floor - North
8. 1st Floor - North
9. 4th Floor - South
10. 2nd Floor - South

Norfolk
1. HVAC Return
2. 8th Floor
3. 7th Floor
4. 6th Floor
5. 5th Floor
6. 4th Floor
7. 3rd Floor
8. 2nd Floor
9. 1st Floor

Ann Arbor
1. HVAC Return
2. 4th Floor Return
3. 3rd Floor Return
4. 1st & 2nd Floor Return
5. Lobby
6. Post Ofice

Fayetteville
1. 1st Floor
2. 2nd Floor
3. 3rd Floor
4. 4th Floor
5. 5th Floor
6. Courtroom - 5th Floor

Huron
1. North Return
2. East Return
3. 4th Floor - North
4. 3rd Floor - North
5. 2nd Floor - North
6. 1st Floor - North
7. 4th Floor - East
8. 3rd Floor - East
9. 2nd Floor - East
10. 1st Floor - East

Pittsfield
1. 1st Floor Return
2. 2nd Floor Return

Table 2. Location of Tracer Gas Sampling

Temperature Bin	Ventilation Occupied	Dampers Closed (Wind < 2.5 M/S)	Dampers Closed (Wind > 2.5 M/S)
(^{o}C)	(X/HR)	(X/HR)	(X/HR)
(-20 < -10)	0.33	0.27	0.31
(-10 < 0)	0.44	0.33	0.25
(0 < 10)	1.15	0.24	
(10 < 20)	1.29	0.27	0.63
(20 < 30)			

Table 3. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Anchorage, AK

Temperature Bin	Ventilation Occupied	Dampers Closed (Wind < 2.5 M/S)	Dampers Closed (Wind > 2.5 M/S)
(^{o}C)	(X/HR)	(X/HR)	(X/HR)
(-20 < -10)			
(-10 < 0)	0.62	0.36	
(0 < 10)	0.54	0.44	0.49
(10 < 20)	1.69	0.41	
(20 < 30)			

Table 4. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Columbia, SC

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	0.67	0.63	0.67
(0 < 10)	0.65	0.47	0.52
(10 < 20)	1.18	0.48	0.53
(20 < 30)	0.76		

Table 5. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Norfolk, VA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	1.02	0.62	0.78
(0 < 10)	0.93	0.52	0.77
(10 < 20)	0.68	0.36	
(20 < 30)	0.58		

Table 6. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Springfield, MA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)		0.25	
(0 < 10)	0.74	0.30	0.27
(10 < 20)	0.92	0.29	0.34
(20 < 30)	0.59	0.45	

Table 7. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Pittsfield, MA

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)	0.29	0.27	0.26
(-10 < 0)	0.26	0.24	0.26
(0 < 10)	0.25	0.16	0.18
(10 < 20)	0.23	0.12	
(20 < 30)	0.67		

Table 8. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Huron, SD

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)		0.43	
(0 < 10)	0.31	0.31	0.38
(10 < 20)	0.36	0.30	0.30
(20 < 30)	0.66	0.28	0.71

Table 9. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Fayetteville, AR

Temperature Bin (°C)	Ventilation Occupied (X/HR)	Dampers Closed (Wind < 2.5 M/S) (X/HR)	Dampers Closed (Wind > 2.5 M/S) (X/HR)
(-20 < -10)			
(-10 < 0)	0.60	0.57	0.79
(0 < 10)	0.64	0.70	0.81
(10 < 20)	1.92	0.56	0.62
(20 < 30)	0.43	0.46	

Table 10. Average Air Exchange Rates in Various Temperature Bins During Occupied Periods and Unoccupied Periods with Dampers Closed - Ann Arbor, MI

	Smoking	Non-smoking	Design	10% Outside Air
Anchorage	0.67	0.17	-	0.28
Pittsfield	0.42	0.10	0.42	0.32
Norfolk	0.69	0.17	-	0.25
Columbia	0.41	0.10	0.29	0.28
Ann Arbor	0.38	0.09	0.52	0.36
Fayetteville	0.41	0.10	0.94	0.57
Huron	0.49	0.12	-	0.31
Springfield	0.46	0.12	-	0.44

Assumptions: 7 people per 100 ^{2}
Smoking: 10 l/s per person
Non-Smoking 2.5 l/s per person

Table 11. Estimated Minimum Ventilation Rates Required

Building Location	Pressurization Flow at 25 Pa (volumes/hour)	Tracer Gas Decay* Infiltration Rate (volumes/hour)
Anchorage	0.80	0.20 to 0.30
Ann Arbor	0.86	0.55 to 0.65
Columbia	0.67	0.35 to 0.45
Fayetteville	----	0.35 to 0.45
Huron	0.45	0.10 to 0.20
Norfolk	1.36	0.45 to 0.55
Pittsfield	1.07	0.25 to 0.35
Springfield	1.00	0.30 to 0.40

* The values listed correspond to a range of measured infiltration rates with wind speeds less than 1.5 m/s and an outside temperature between 5 and 10 ^{o}C.

Table 12. Airtightness Measurement Results for Eight Federal Buildings.

	Air Penetration Walls	Air Penetration Ceiling	Air Leakage Doors	Air Leakage Windows	Joints Wall Wall	Joints Ceiling Wall	Joints Floor Wall
Anchorage	*			*	*		*
Ann Arbor	*	*		*	*		*
Columbia	*	*	*	*	*	*	*
Fayetteville			*	*	*	*	*
Huron	*		*	*	*	*	*
Norfolk	*	*	*		*	*	*
Pittsfield	*	*		*	*	*	*
Springfield	*			*		*	*

Table 13. Dominant Locations of Air Leakage Sites as Revealed by Thermographic Inspections.

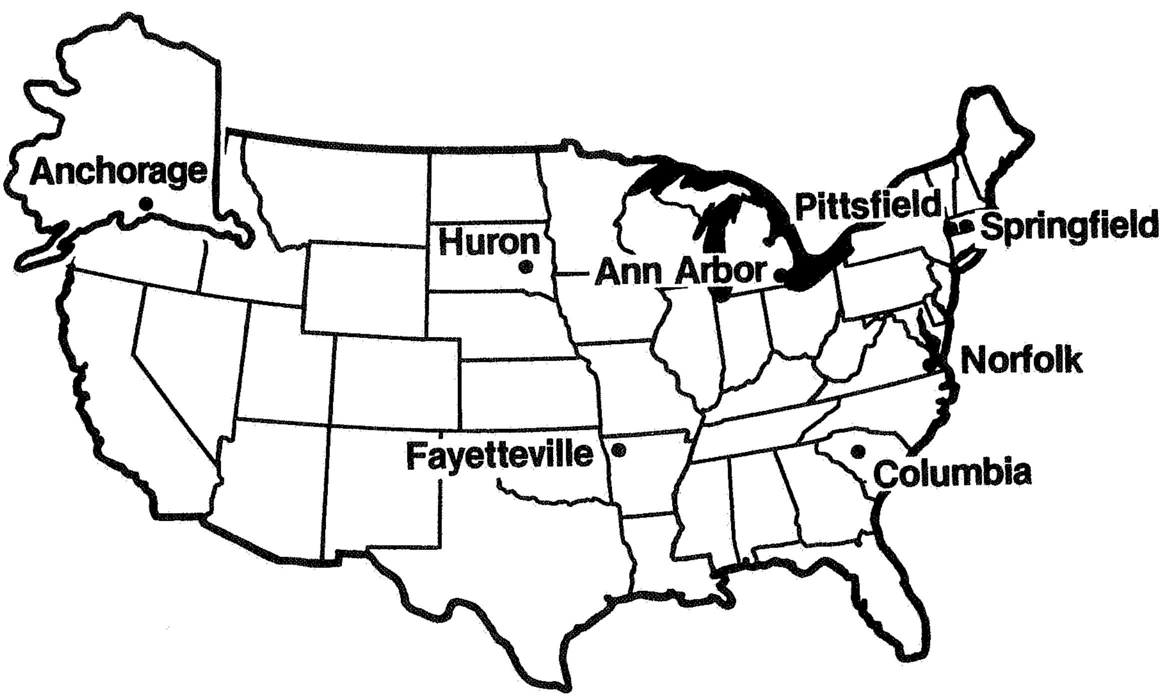


Figure 1. Location of Eight Federal Office Buildings in U.S.A.

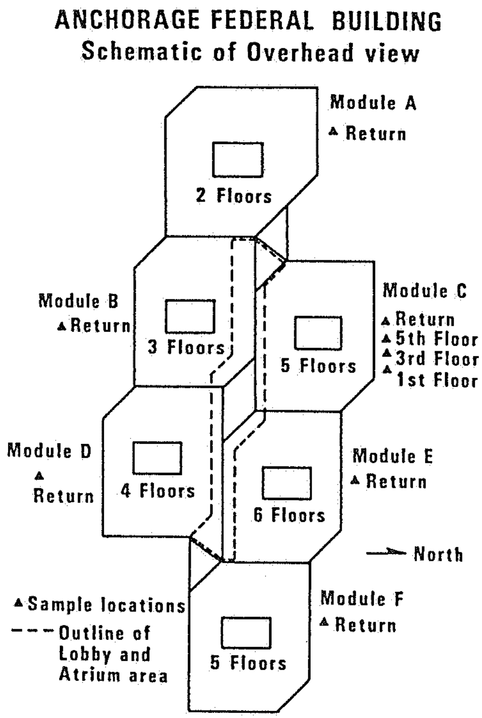
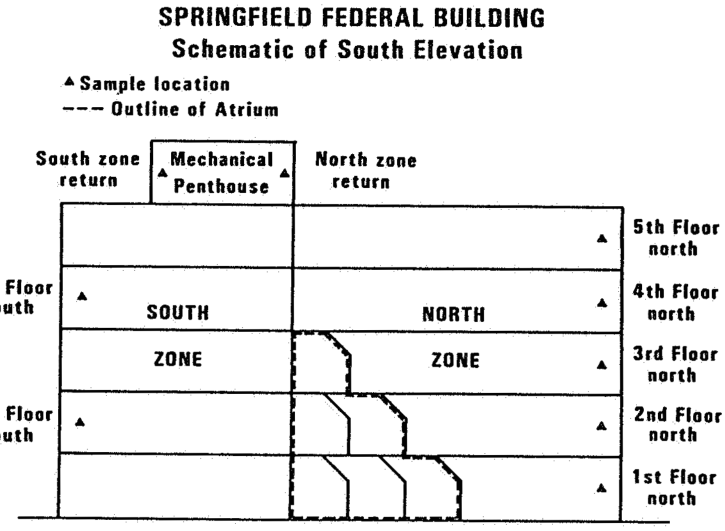
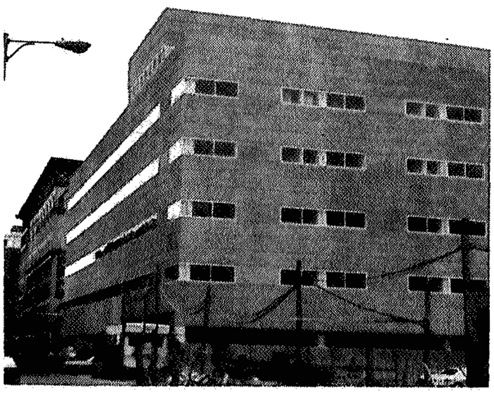


Figure 2. Schematic and Photograph of Federal Building in Anchorage, AK





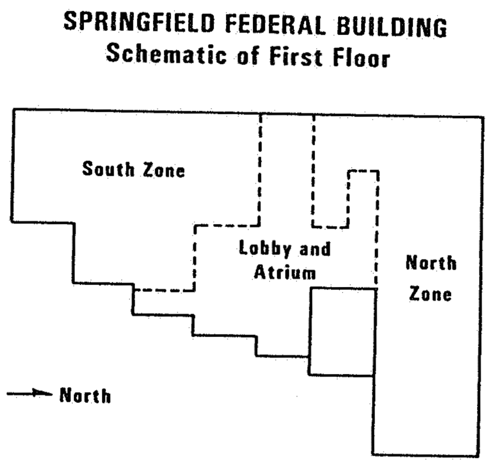
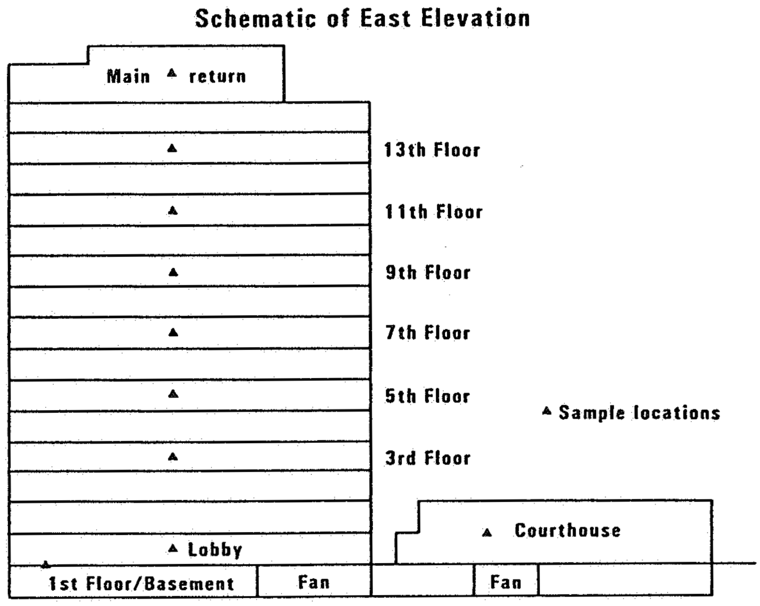
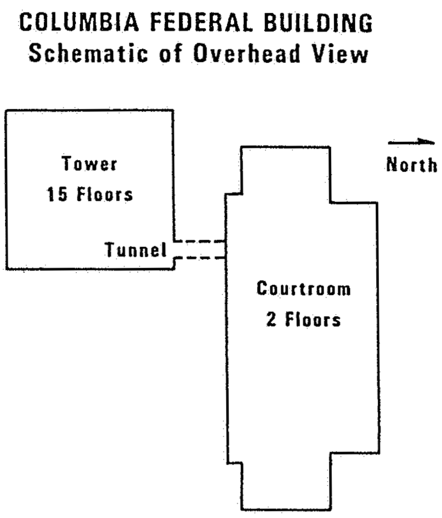


Figure 3. Schematic and Photograph of Federal Building in Springfield, MA





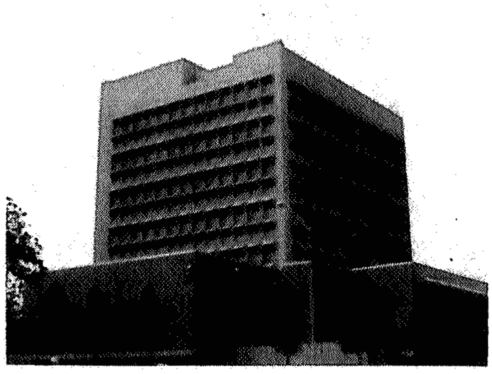


Figure 4. Schematic and Photograph of Federal Building in Columbia, SC

	Air Penetration		Air Leakage		Joints		
	Walls	Ceiling	Doors	Windows	Wall Wall	Ceiling Wall	Floor Wall
Anchorage	*			*	*		*
Ann Arbor	*	*		*	*		*
Columbia	*	*	*	*	*	*	*
Fayetteville			*	*	*	*	*
Huron	*		*	*	*	*	*
Norfolk	*	*	*		*	*	*
Pittsfield	*	*		*	*	*	*
Springfield	*			*		*	*

Table 13. Dominant Locations of Air Leakage Sites as Revealed by Thermographic Inspections.

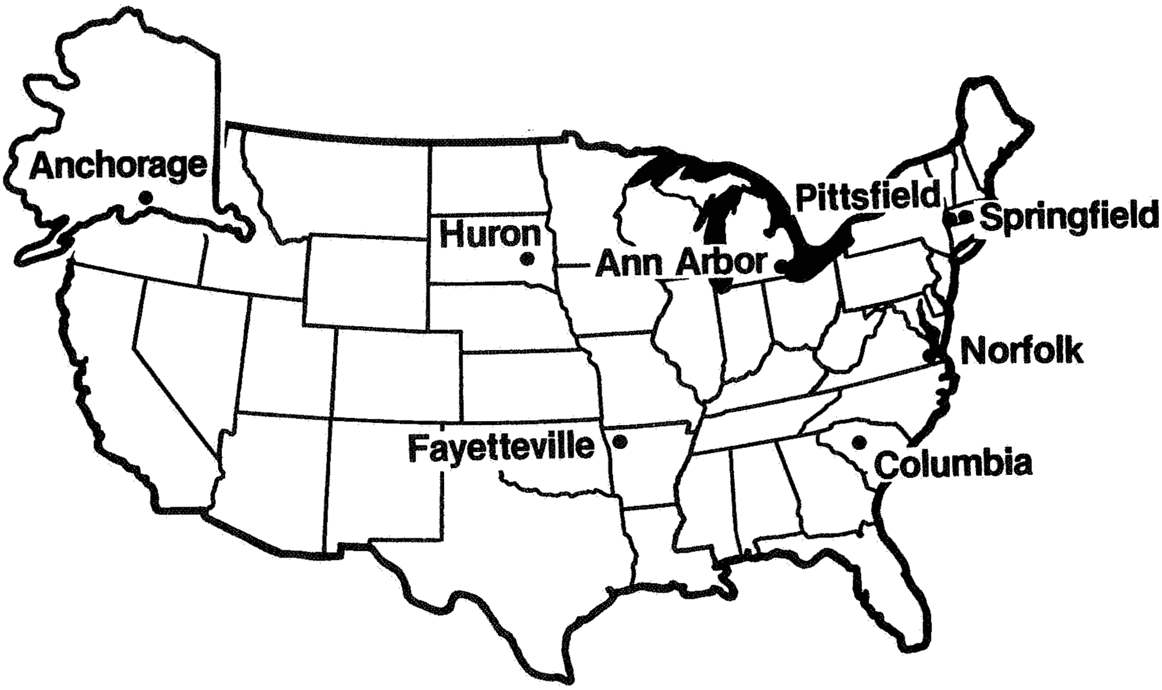


Figure 1. Location of Eight Federal Office Buildings in U.S.A.

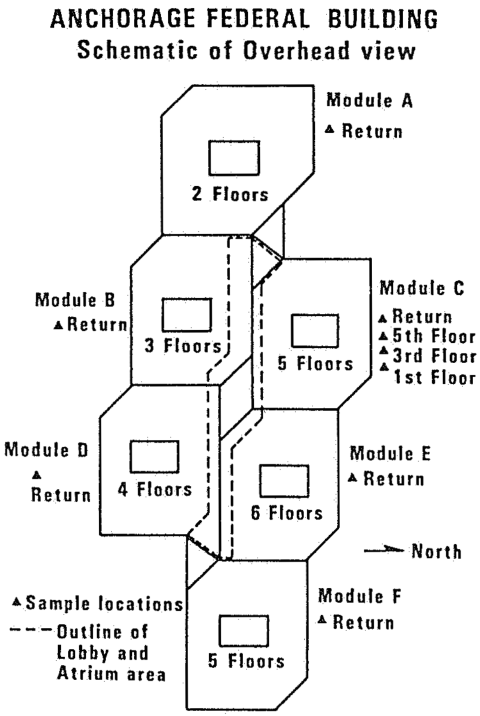
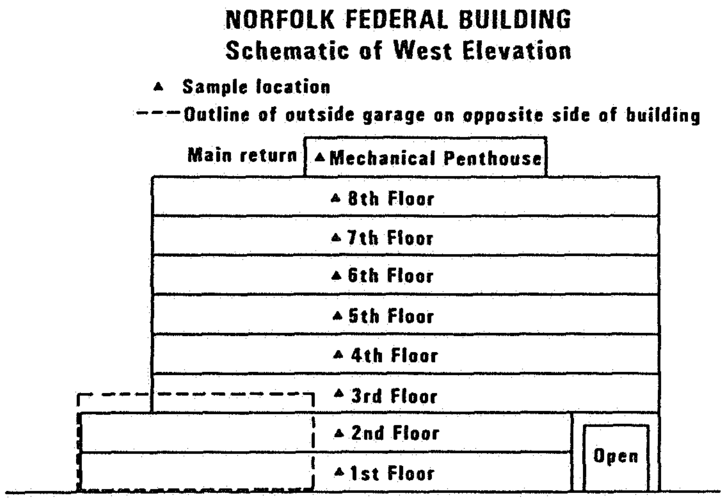
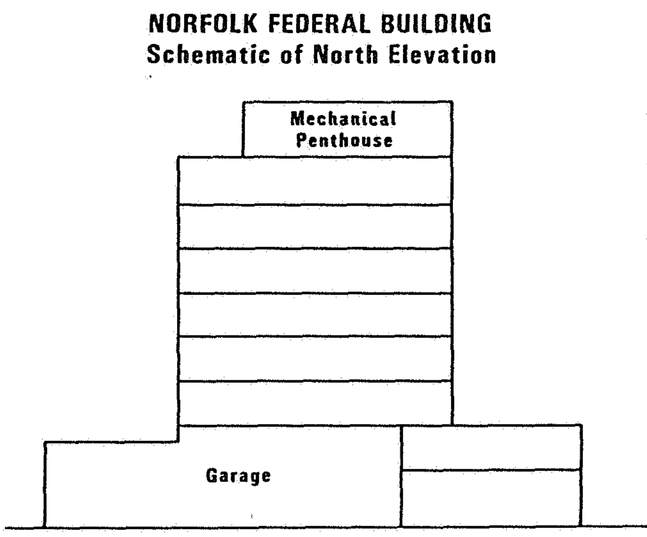


Figure 2. Schematic and Photograph of Federal Building in Anchorage, AK





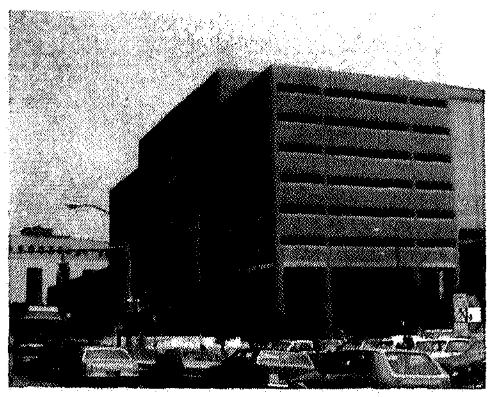


Figure 5. Schematic and Photograph of Federal Building in Norfolk, VA

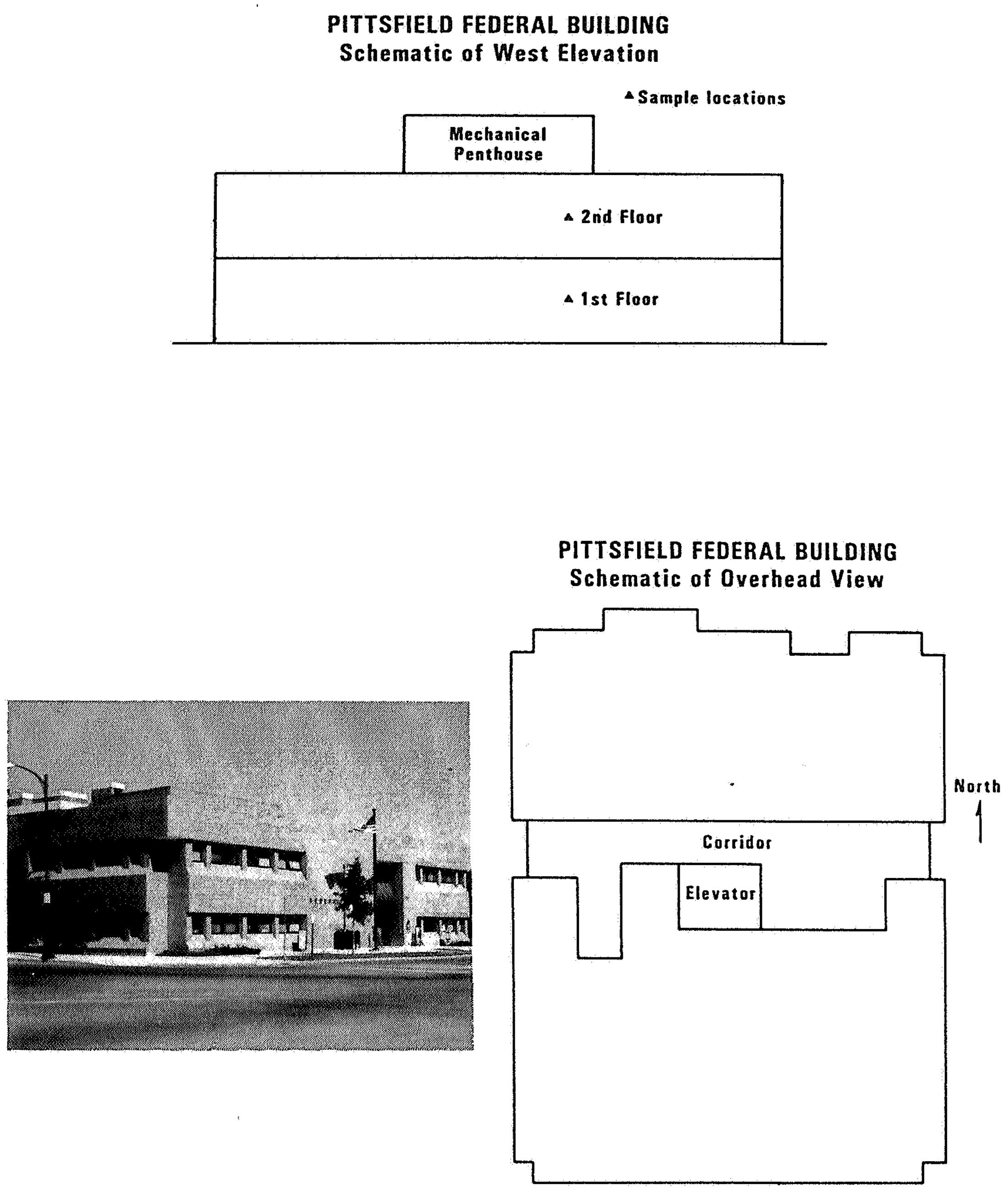
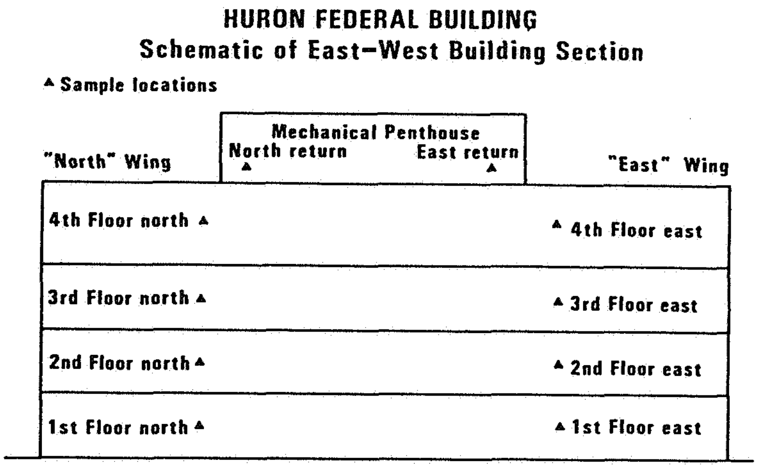


Figure 6. Schematic and Photograph of Federal Building in Pittsfield, MA



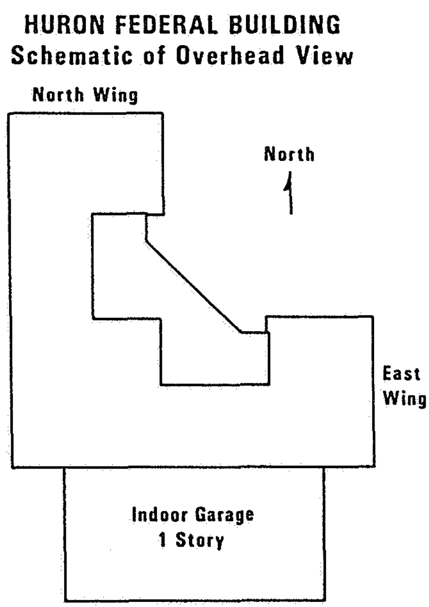
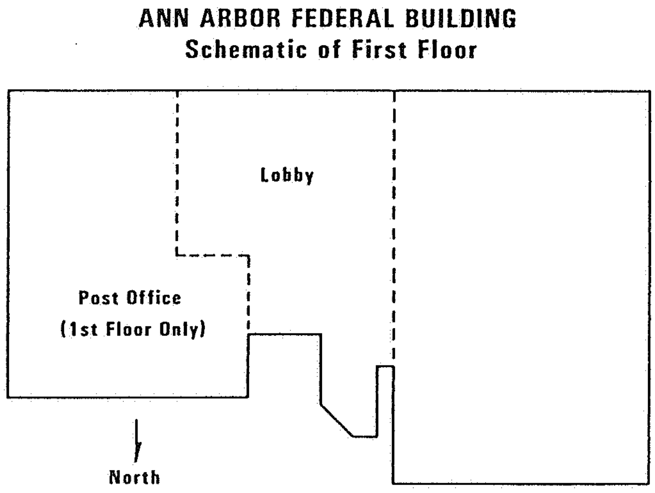
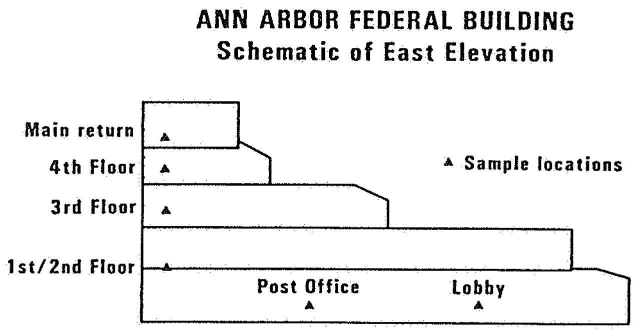


Figure 7. Schematic and Photograph of Federal Building in Huron, SD





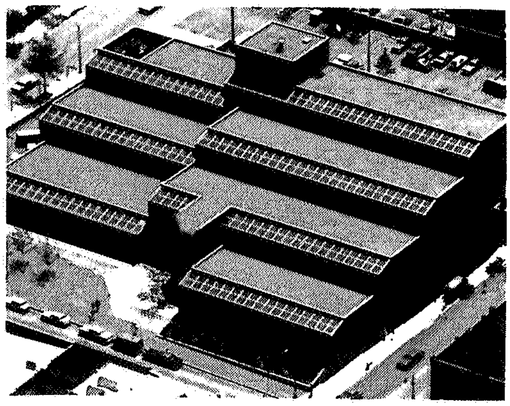
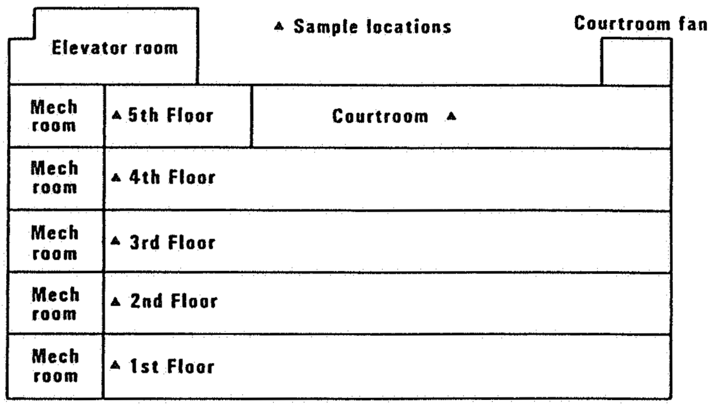
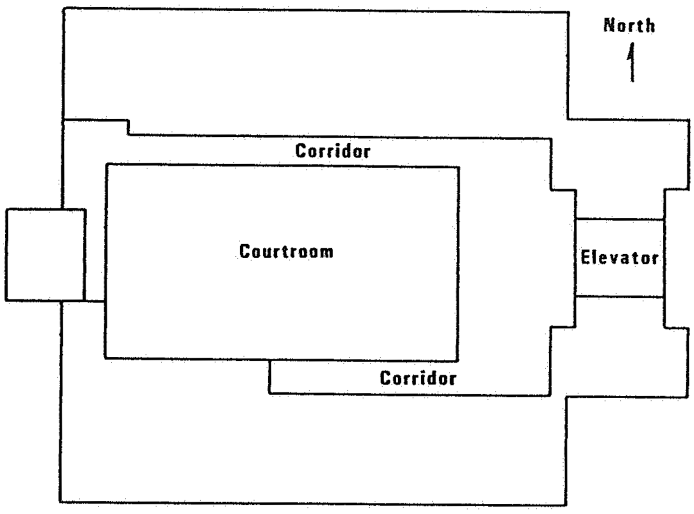


Figure 8. Schematic and Photograph of Federal Building in Ann Arbor, MI

FAYETTEVILLE FEDERAL BUILDING
Schematic of North Elevation



FAYETTEVILLE FEDERAL BUILDING
Schematic of Fifth Floor



FAYETTEVILLE FEDERAL BUILDING
Schematic of First Floor

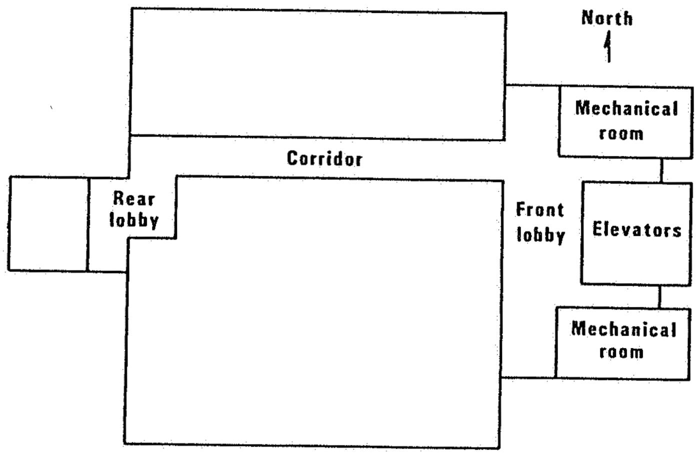


Figure 9. Schematic and Photograph of Federal Building in Fayetteville, AR

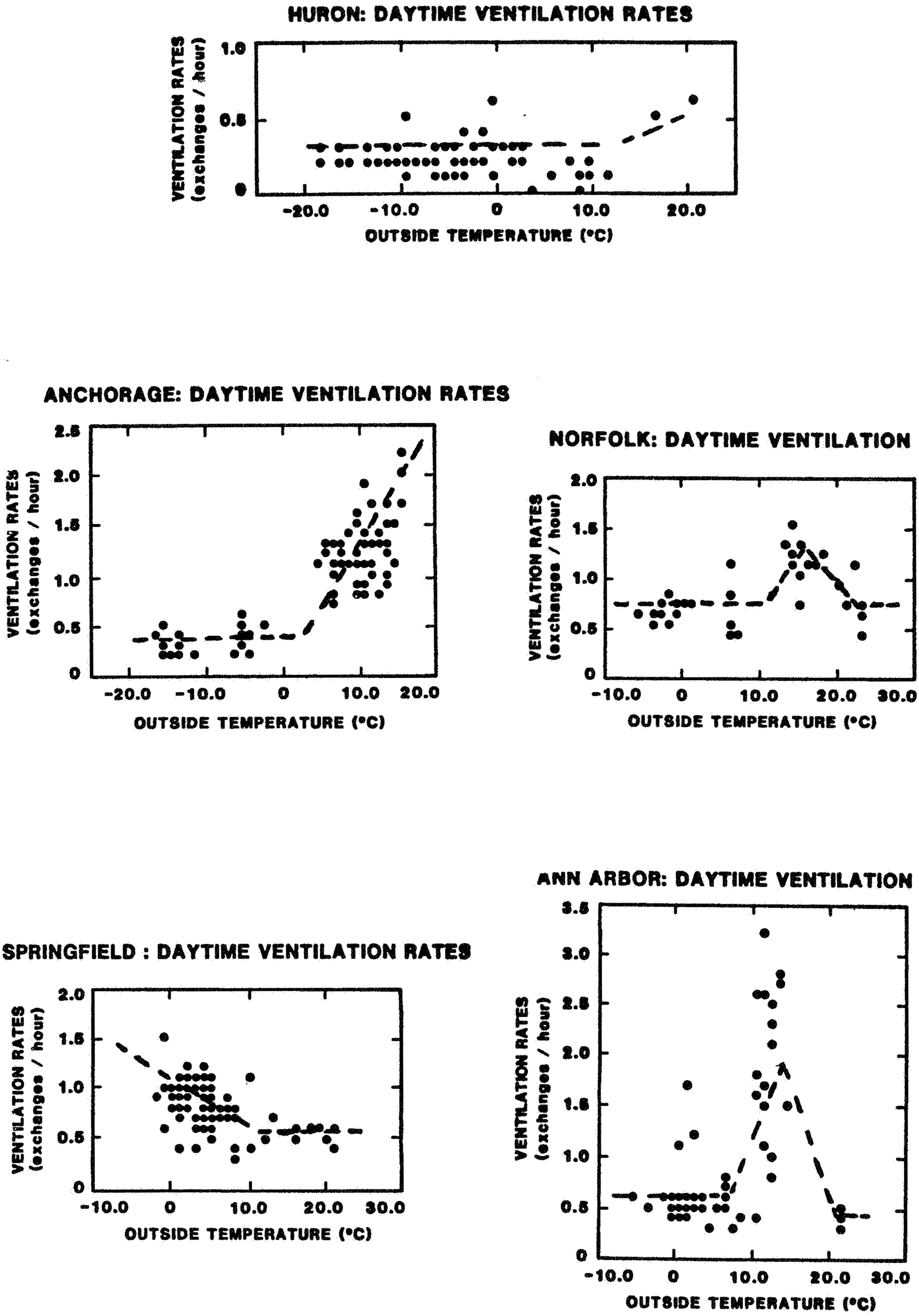


Figure 10. Ventilation Rates Versus Outdoor Temperature for Various Office Buildings

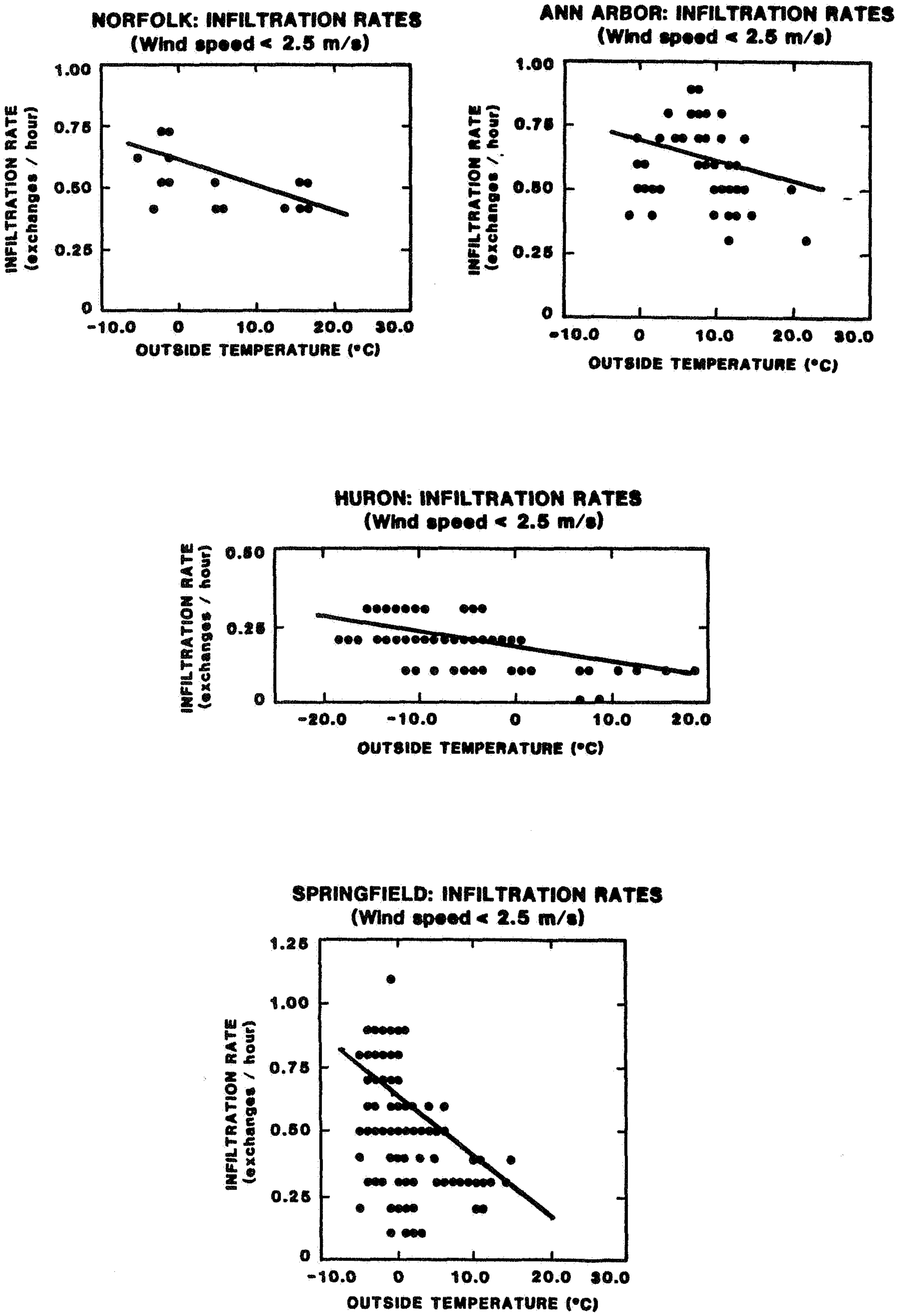
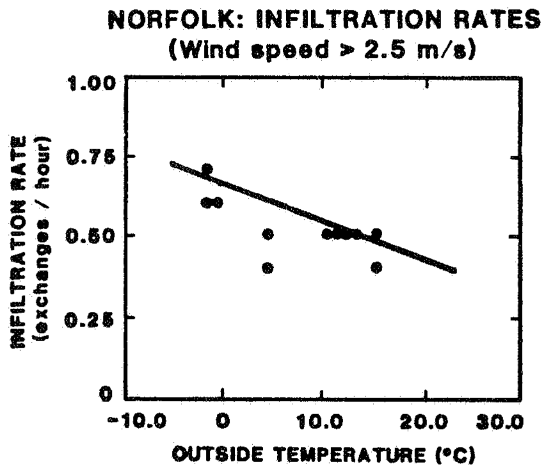
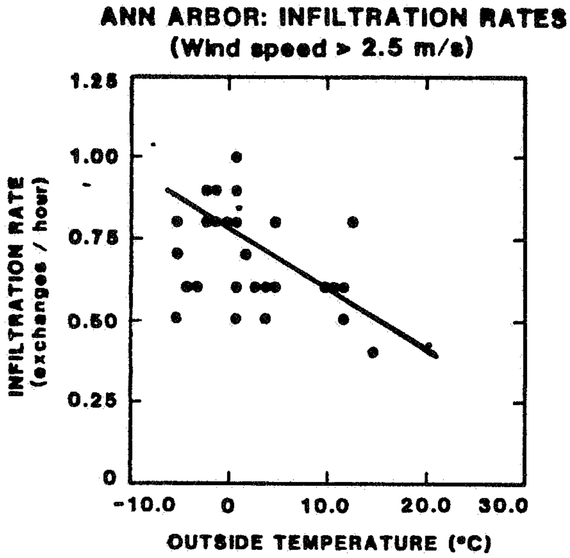


Figure 11. Infiltration Rates Versus Outdoor Temperature for Wind Speed Less Than 2.5 M/S





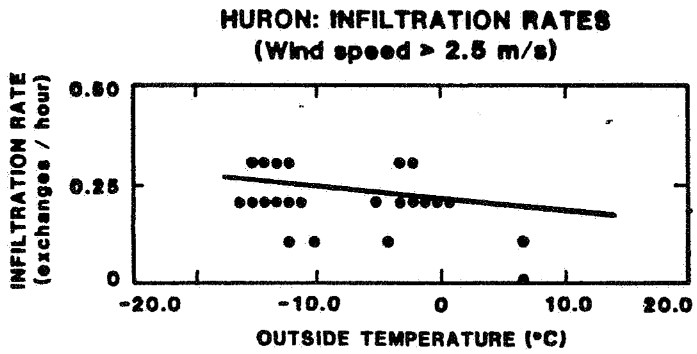


Figure 12. Infiltration Rates Versus Outdoor Temperature for Speed Greater Than 2.5 M/S

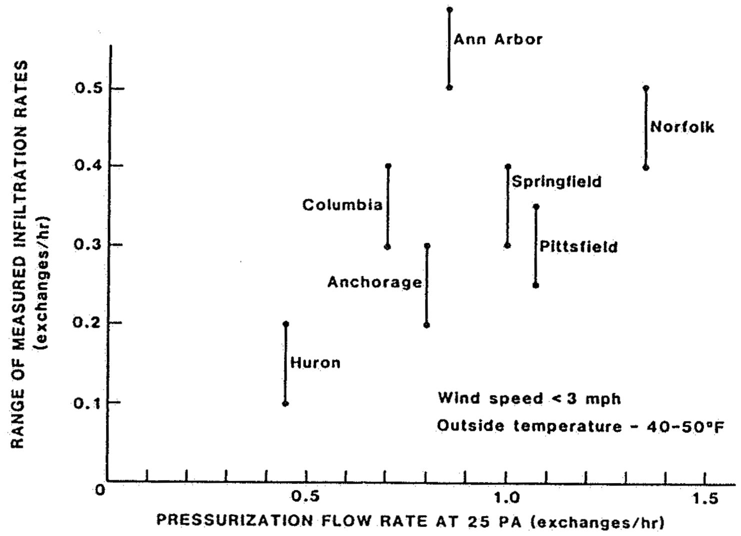


Figure 13. Correlation of Air Infiltration Rates Versus Induced Air Exchange Rates at 25 Pa

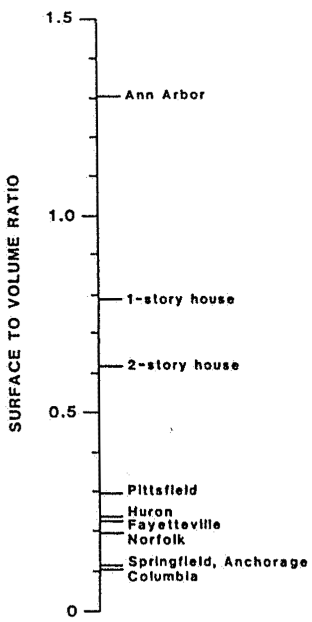


Figure 14.
Distribution of Surface to Volume Ratio Among Federal Offices and Residences

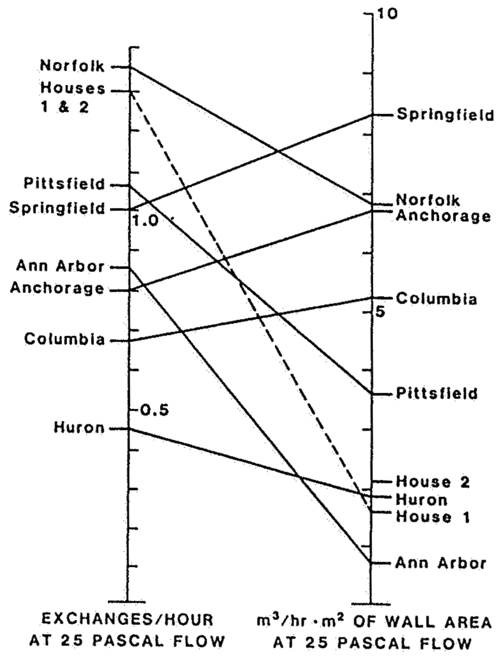
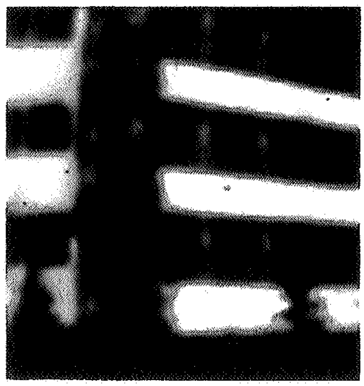
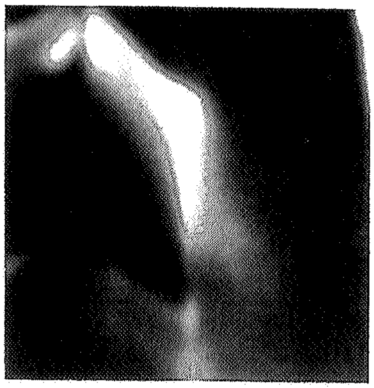


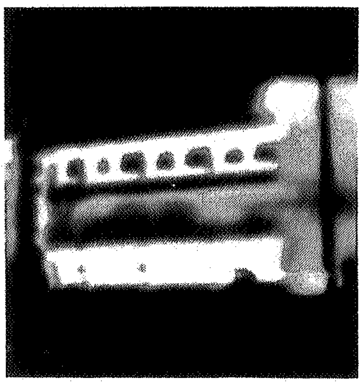
Figure 15.
Pressurization Test Results Comparision of Ranks



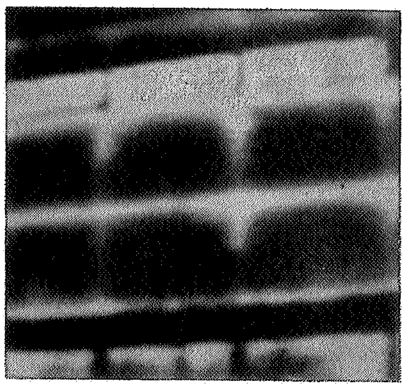
Anchorage - Air Leakage at Corner Columns



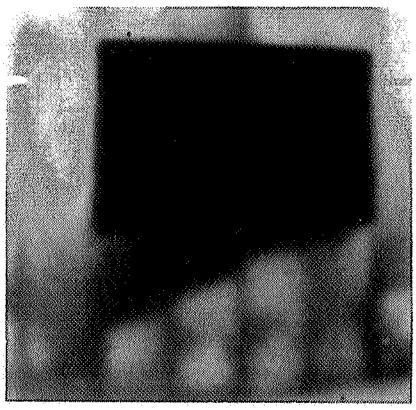
Huron - Air Leakage for Wall-Wall Corner



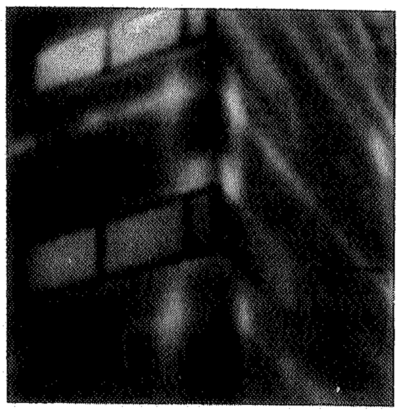
Pittsfield - Air Penetration in Wall



Ann Arbor - Air Penetration at Wall-Floor Joint



Columbia - Interior Air Penetration from Window



Springfield - Air Leakage Corner Column, Wall-Floor Joint and Window Frames

Figure 16. Sample Thermograms Showing Air Leakage Sites in Office Buildings